Measuring the Polarization of the Cosmic Microwave Background: CMB RoPE

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Foreword & Acknowledgements

This senior thesis is a product of two years of collaborative work between many individuals. In this paper I address the background of CMB physics and the reasons for pursuing the polarization of CMB. Although I have tried to give a general overview of the RoPE project, this paper in no way is a complete account of RoPE. I give detailed descriptions in areas where I have made contributions, but I have left out many details where I have felt that others were more qualified to write about.

In the first three sections I introduce CMB and CMB polarization and their place in the exciting field of cosmology. I hope I have conveyed a sense of importance of the topic and its far-reaching consequences. In the remaining sections I describe our project and its various aspects, including the numerous problems we encountered in the process.

The following pages would not have been possible without the support and nagging of Professor George Smoot. I thank him for giving us the complete freedom to wander in the dark and trip over things continuously. I have learned much more than I could have under constant scrutiny as a result. I also thank my fellow students who have worked on this project with me even when things were looking dismal and greener pastures were elsewhere to be found. Mike for his vacuum expertise, Asad for going from start to finish with me, Peter for learning to say ‘dude’ with an Irish accent, Ian who brought much-needed seriousness to the group for a summer, Rona and Ben for their professionalism and diligence, Meridith for being a cool drummer when the rest of us were just geeks, Raanan for his unbridled enthusiasm and making up for our sugar-deficit, Abraham for questioning my judgments when no one else did, John Gibson for all the helpful notes and scribbles, Jodi and Azriel for their willingness to get up from whatever they were doing to help out, Professor Herbert Steiner for all the encouragements, Robert & Colleen Haas Scholarship for giving me financial support, Erik, Nish and James for taking on a project with an uncertain future, and finally INPA for giving me a fabulous work environment and some good cheese to go along with it. Thank you.

1. Introduction

The cosmic microwave background radiation (CMBR) was discovered serendipitously in 1965 by Penzias and Wilson. Ever since, a series of increasingly sensitive measurements have resulted in ever-stringent cosmological models of the universe's evolution, culminating in the final results of the COBE satellite (Smoot *et al.* 1992). The importance of CMB in our understanding of cosmology cannot be overstated. It gives us one of the best evidence of big bang. In fact, such a background radiation was predicted to exist as a consequence of the big bang nucleosynthesis much earlier (Alpher, Bethe & Gamow 1948).

The significance of the CMB can be better appreciated when one considers what it exactly is. The expansion of the universe tells us that once it was hotter and smaller than it is today. Going back enough in time, one can expect the universe to have been so hot that matter and light existed in a photon-baryon plasma made up primarily of protons, electrons and photons. Due to the free electrons, the photons were constantly scattered and therefore tightly coupled to baryonic matter. As the universe expanded, it cooled sufficiently enough to form neutral hydrogen, which was accompanied by a drastic drop in opacity.[1] Photons thus uncoupled to matter still fill the universe around us, with a redshift of 1065±80.[2] Looking into space, we see this event as a boundary between opaque and transparent universe. CMB photons that travel to us from this boundary then is the image of this surface. This surface is called the last-scattering surface. The optical depth as a function of redshift can be determined accurately independent of many of the cosmological parameters (W_b, W, H_0, *etc.*) that are of interest, making CMB ideal for studying cosmology.

Since the CMB is essentially a snapshot of the last scattering surface, studying the properties of the CMB along with knowing the thermal conditions of the universe at redshift 1100 tells us much about the matter-energy distribution of the early universe and the rate of its expansion.[3] Although the CMB is nearly uniform in the sky with an equivalent temperature of 2.728±0.004 K (Fixsen *et al.* 1996), slight variations, or anisotropies, exist at the 10^{-5} K level at various angular scales. This temperature anisotropy, which is sensitive to W_b, W, H_0, and *?*, was first successfully measured by COBE DMR and more recently by groups such as MAXIMA, Boomerang, and others. In the near future MAP and Planck satellites will map the temperature anisotropy of the CMB with unprecedented precision.

However exciting this is, measuring the temperature anisotropy alone will not tell the whole story of the early universe. This is because there are many physical processes that may end up having the same temperature anisotropy signature. Different sources of the primordial fluctuations can be undistinguishable by just looking at the anisotropy data. A way to distinguish between these processes that are responsible for the structures we see today is needed.

2. CMB Polarization and Its Significance

A measurement of the polarization of CMB is just the thing that is needed for breaking the degeneracy of cosmological models. Kinematically, we can categorize the physical processes responsible for the fluctuations into three different sources: scalar, vector, and tensor modes.[4] Scalar mode refers simply to the scalar distribution of hot and cold regions in the primordial photon-baryon fluid. Vector mode arises from doppler shifts in temperature due to non-zero gradients in the velocity field of the fluid. Finally, the tensor mode refers to the fluctuations due to gravitational waves that stretch and contract the spacetime. These different modes will have unique polarization signatures, enabling one to discern the degree to which each contribute to the temperature anisotropy.

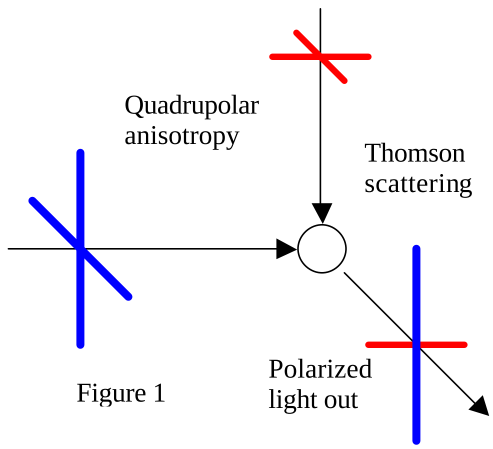

Figure 1

The reason this is possible is essentially because polarization of CMB has only one cause: the quadrupolar variation in temperature as seen by the scattering electron. Thomson scattering of unpolarized light can cause polarized scattered light by the following process. Incoming polarized component will be maximally scattered in the direction that is perpendicular to the incoming light and with the polarization vector aligned in the same direction. Figure 1 shows how this can cause unpolarized light distribution with quadrupolar anisotropy to be linear polarized through Thomson scattering. It is easy to see that only quadrupolar anisotropy can cause this, as any other angular distribution will end up canceling out the outgoing polarization.

CMB polarization is useful for a number of other reasons. Since polarization is more immune to evolutionary effects between here and the last scattering surface than the temperature anisotropy, it probes the early universe in a much more direct manner. Also, polarization power spectrum can be used to determine the ionization history of the universe, which is difficult to distinguish from parameter normalizations when looking solely at the temperature fluctuations (Hu & White 1997). Even more exciting is that polarization information can be used to test the consequences of inflation directly. Topological defect models and inflationary models predict different polarization power spectra, and this can be a powerful way to rule out competing cosmological models.[5 6]

Measuring the polarization of the CMB is therefore crucial to improving our understanding of the early universe. Not only will it provide independent and complementary information to that of the temperature anisotropy, but it will also break degeneracies in the current cosmological models. Important questions regarding inflation and the ionization history of the universe can be approached experimentally.

3. Experimental Challenges

There is a very good reason why the polarization of the CMB has not been measured yet. Until recently, expected level of polarization was much smaller than what was available technologically: even the most favorable models (from the point of view of those trying to measure it) predicted that CMB is only polarized at the 10μK level. More realistically, CMB polarization is expected to be at a few μK. Many experiments in the past have tried this daunting measurement, only to set an ever-decreasing upper limit on the polarization of the CMB. Most recent upper limit is 16 μK (Netterfield *et al.* 1995).

The challenges facing the experimentalists are many-fold. First and foremost, one must design a system capable of reaching μK-sensitivity. The technology to accomplish this became available only recently. This means careful shielding from ambient and line noise sources as well as isolation from vibrations and magnetic coupling. One must also take into account foreground signals that obscure the CMB polarization. Galactic contamination in the form of synchrotron emission, which is expected to be highly polarized, is the most prominent foreground source. This means multiple frequency coverage is needed to subtract out the synchrotron radiation, which has a different spectral dependence from the Planck-distributed CMB. One relative advantage is that realistic efforts at ground observation is possible when measuring the CMB polarization. This is because the atmosphere is expected to be negligibly polarized, far below the level of the signal.[7]

4. Overview of RoPE

Beginning in January 1998, I have been involved in designing and operating an experiment to measure the polarization of the CMB along with a number of other undergraduates. The basic aim of this experiment is to construct a sensitive radio telescope capable of polarization measurements and drift-scan through the zenith at altitude 38º N. We employ an off-axis parabolic 1.8 M aluminum dish with 22.3º offset coupled to a conical microwave feedhorn that is linearly polarized. A total power receiver is used at 8-10 GHz bandwidth.

The observation strategy is to rotate the entire linearly polarized telescope slowly at 6 rpm. This rotation speed was chosen so that the modulation of the polarization signal from rotation would be above the 1/f noise of the receiver. As can be seen in Figure 2, the feedhorn, the receiver electronics, and the data acquisition module reside on a tower at the end of the horizontal beam.

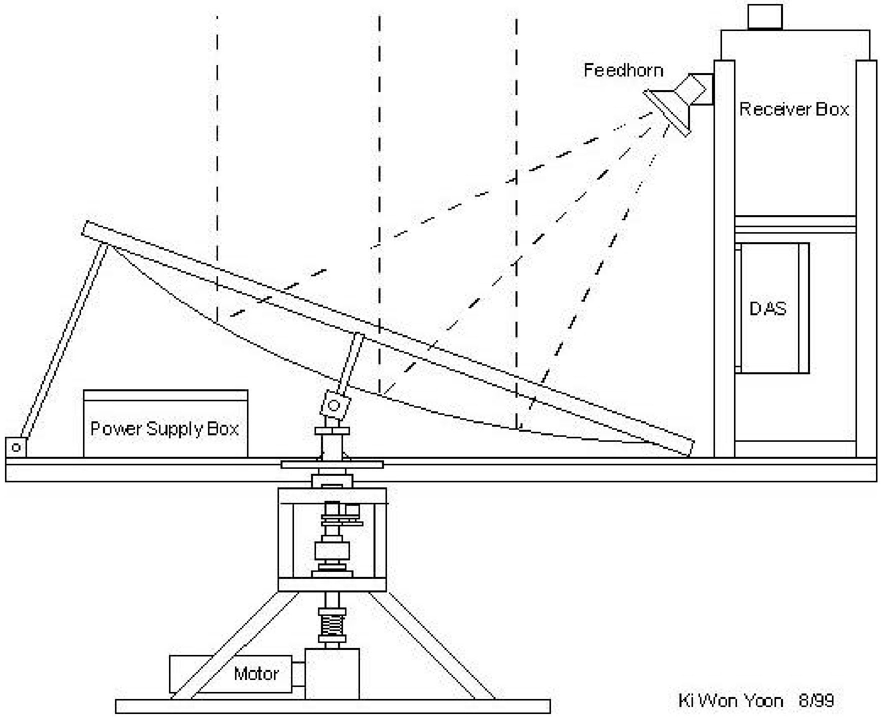

Figure 2

A power supply box was mounted on the other side for better balancing. A slipring unit on the rotating shaft relays AC power up and digitized serial data down to the computer. In addition to the signal voltage, we also monitor various temperatures of the components to make sure they are thermally stable and the shaft angle is measured by a digital angle encoder with ~1º resolution to determine the angle of polarization of the beam. All this information is then sampled and digitized by the data acquisition module (DAS) as a serial packet every 0.43 s and read into a computer. This sampling rate combined with our rotation rate of 6 rpm means that we sample every 15º of rotation of the beam.

The voltage output proportional to the total incident intensity filtered with the linearly polarized beam combined with the shaft angle of measurement can then be fitted for the Stokes parameters Q and U for each pixel on the circular ring.[8] Fitting for the Stokes parameters directly instead of polarization angle and intensity of polarization gives you the advantage of being able to average the parameters over pixels. This is possible because the Stokes parameters are linear quantities, whereas angles and degree of polarization are not.

5. Experimental Design

In this section I summarize specific areas of the RoPE project on which I have spent a significant amount of time. It is in no way intended to be a complete description of the project as a whole. Specifically, the major areas not described in this thesis are as follows. 1. Vacuum and cryogenics systems: we employ a small liquid nitrogen dewar to cool the 1st stage amplifier down to 77 K to reduce system noise. I was not heavily involved in the technical aspects of maintaining a vacuum system and dealing with cryogenics. 2. Mechanical design: This involves the structural design of the telescope and specifically deals with the rotation mechanism. Please refer to Asad Aboobaker's senior thesis for more detail on this subject. 3. Feedhorn/SMA coupling: The problem of coupling the circular feedhorn to an SMA connector was a huge and difficult process of obscure theory and trial and error combined with ingenuity and diligence on the part of Asad. Again, more detail on this subject can be found in his thesis.

5.1 Microwave Receiver

Our receiver is a total power receiver as described in *Radio Astronomy* by Krauss. This type of receiver was chosen for both its simplicity and its noise advantage over other types of receivers. Achievable RMS noise temperature of the receiver is given by

$$T_{rms} = \frac{K_s T_{sys}}{\sqrt{\Delta n t}}$$

where ?? is the frequency bandwidth of the system, t is the time in seconds observing a given pixel, and K_s is a dimensionless factor that takes into account different receiver designs.[8] For a total power receiver, K_s=1, whereas for a correlation receiver, for example, K_s=1.4. Using hot/cold load test, we determined our system temperature to be T_{sys} = 80 K. This gives our achievable sensitivity of

$$T_{rms} = 1.8 t^{-1/2} mK$$

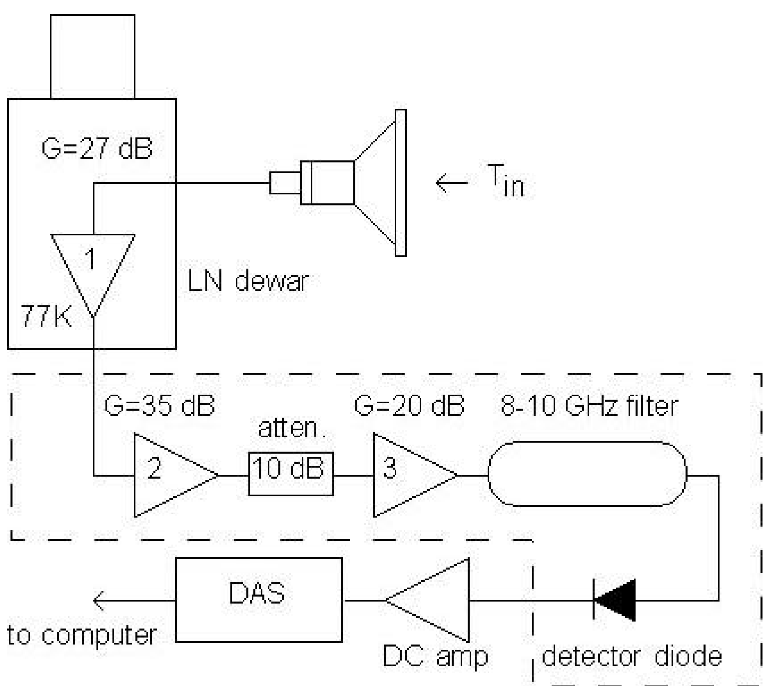

Figure 3

A block diagram of our receiver is seen in Figure 3. As mentioned earlier, the 1^{st} stage amplifier is cooled to 77 K using a liquid nitrogen dewar. The 1^{st} stage low-noise HEMT amplifier was received from NRAO. It has a gain of 27 dB at 77 K with a bandwidth of 8-10 GHz. If cooled to 15 K, it is capable of achieving a system temperature of 10 K. The signal from the feedhorn is amplified by the 1^{st} stage and subsequently amplified and filtered by the "warm" components. Both the 2^{nd} and 3^{rd} stage amplifiers were purchased from JCA. The detector diode takes in incoming power and outputs a voltage proportional to it. The conversion ration is on the order of mV/µW. All the components within the dotted line are kept in a thermally insulated box mounted on a temperature-controlled "hot plate". This is to avoid sensitivity loss due to gain fluctuations caused by temperature drifts. The output of the detector diode is further amplified by a custom-designed DC amplifier and digitized by the DAS.

5.2 Feedhorn & Optics

Using a single offset-parabolic dish is useful because the feed structure does not block the beam pattern on the sky. Our 1.8 M aluminum dish was ordered from Andersen Manufacturing Inc. To achieve high sensitivity and be immune from the ambient radiation of 300 K, I had to design a feed structure that would significantly under-illuminate the dish. Specifically, the design parameters were:

1. 10 dB fall-off at 35º from axis; 20 dB fall-off at 53º.
2. No sidelobes out to 100º from axis.
3. less than -20 dB reflection throughout 8-10 GHz bandwidth.
4. Linearly polarized, with cross-polarization around -80 dB.

Following the procedure and analysis outlined in Clarricoats & Olver (1984), a conical corrugated aluminum horn was designed.[9] The design of the horn was simulated to calculate the 10 db and 20 dB points using spherical wave expansion method. This was done using the Mathematica software. This analysis yielded the 10 dB and 20 dB points as 34º and 54º respectively. In addition, the simulation showed no sidelobes or backlobes in the radiation pattern. After the waveguide/SMA transition was successfully designed, the feedhorn was tested for the above design parameters.

To test the beam pattern, we set up a transmitting horn that was polarized and far enough away to be an effective point source. We then measured the response of our horn as a function of tilt in both E- and H-plane directions. The normalized measured E-plane beam pattern is shown in Figure 4. The design of the horn was successful in achieving the needed beam pattern and eliminating sidelobes.

The reflection of the horn was tested using a frequency synthesizer and a scalar network analyzer to see how much of the power injected into the horn for broadcast was reflected back. This test showed that the horn was also successful in achieving good efficiency. Most of the reflection was due to the waveguide/SMA transition which we were not able to improve to less than -20 dB for the entire bandwidth of 8-10 GHz.

Cross-polarization was tested by having a broadcast horn mounted in two positions with respect to the RoPE feedhorn: one in which the polarization direction was aligned, and the other in which the directions were perpendicular. The drop in response when the polarization directions were orthogonal was below the sensitivity level of the detectors.

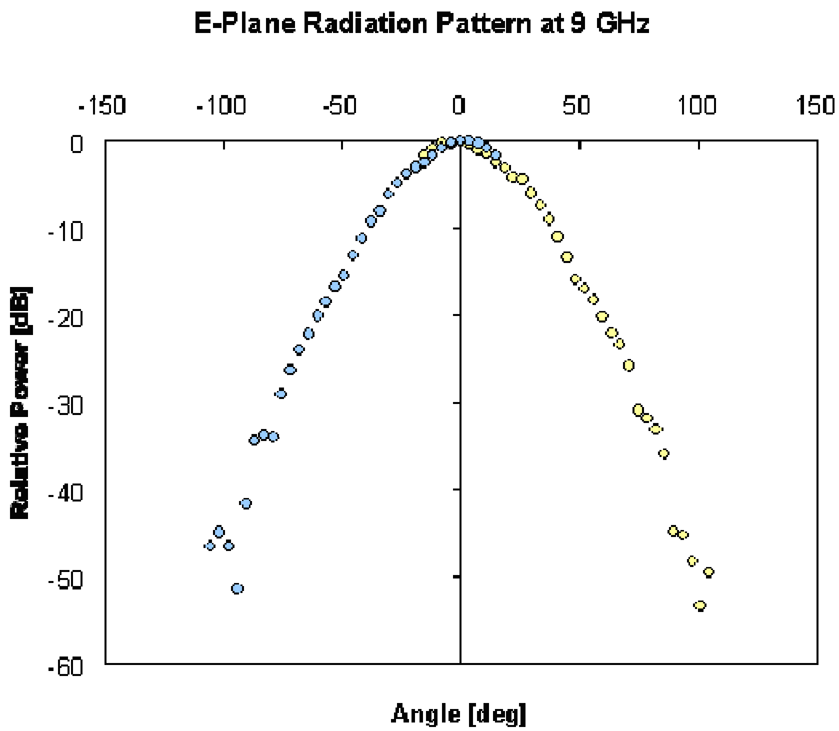

Figure 4

One final test was done to determine where the focus of the dish should line up with the horn. This must be done such that at far distances from the horn where the EM waves from the horn is spherical, the center of the sphere of the origination of the horn lines up with the focus of the dish. Usually for narrow angle flare horns, this point can be taken to be at the aperture of the horn with good approximation. However, for our horn which has a semi-flare angle of 45º, this is not true. To determine the phase center of the horn, we set up a receiver horn the output of which goes to a phase detector. By broadcasting from our horn and rotating it at various axes, one must determine the axis of rotation where the phase of the output at the detector remains constant. This was done and the phase center was determined with suitable accuracy. This position also agreed well with the predicted value that I calculated.

5.3 DC Amplifier

Even after all the amplification of the microwave receiver, the signal must be further amplified because the polarization signature that we are looking for is so small. The problem is that the expected output is a very large DC offset with a small sinusoid riding on it corresponding to the modulated polarization signature. One must first get rid of the DC offset and amplify only the high frequency (above 0.1 Hz) components of the signal without adding significant amount of noise. An initial design for such an amplifier was furnished by John Gibson and modified and made by me.

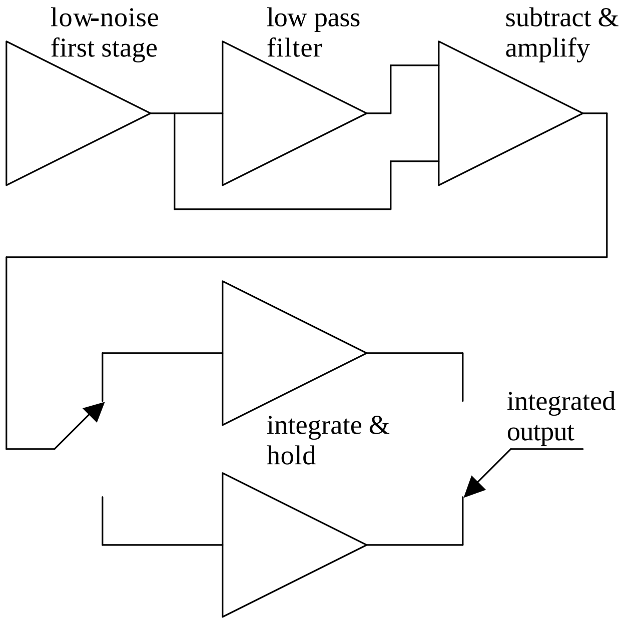

Figure 5

The basic schematic is shown in Figure 5. Since data are sampled every 0.42 seconds, we divide up the signal into even and odd frames where they are alternately integrated and held for 0.42 seconds. For the 1st stage DC amplifier we use the low-noise, low-offset AD521 amplifier. The switching of the signals and resetting of the integrators are done by an accompanying digital circuitry which is in turn governed by the DAS. The output of the DC amp is then the amplified and integrated noise present at the input with the DC offset subtracted off.

5.4 Data Acquisition System

The DAS used for this project was acquired from pre-existing system designed for the MAXIMA experiment. The design was done by John Gibson. The DAS consists of a control module, analog input module, digital words module, and serial-to-RS232 module. The control module has an EPROM program that defines which channels get sampled in which order and how they are packaged as an output and, among other things, supplies the other modules with power, bus signals, and clock signals. The analog module has 16 isolated differential analog inputs with digitization resolution of 16-bits. The digital module is capable of sampling two 16-bit parallel digital words. Finally, the RS232 module takes all the programmed channels that have been read off and packages in a serial format that can be understood by a PC computer.

To reduce the noise in the receiver signal, the output of the DC amp is sampled many times within one frame and afterwards averaged. All other non-critical data such as the outputs of the temperature card and the cryodiode card are only sample once every frame. The output of the shaft encoder, which is a 10 bit digital word, is sampled by the digital module and sampled once a frame according to our EPROM program. The control module also packages into the data a 32-bit frame number.

5.5 Temperature Regulation

Accurate temperature regulation is crucial because the signal we are trying to measure is so small. Any temperature fluctuations in the temperature of the components will result in a corresponding gain fluctuation or changes in the characteristics of the passive components. Our temperature regulation scheme covers two separate areas: one is the 1st stage microwave amplifier, and the other is the 2nd and 3rd stage amplifiers and the detector diode.

The 1st stage amplifier is maintained at a constant temperature by mounting it in a liquid nitrogen dewar. Since the nitrogen evaporates at a fixed temperature, we can maintain the constant temperature as long as the dewar is prevented from warming up. This necessitates daily refilling of the dewar and a constant lookout for vacuum leaks.

The 2nd, 3rd stage amplifiers along with the microwave filter and the detector diode is maintained at a temperature of 35°C by nesting it in a box within a box and using a two-stage temperature regulation system. The larger outside box is regulated at roughly 25°C by using a Peltier cooling device from Melcor with a feedback that switches the heat pump from cooling to heating and vice versa. The warm components are mounted on an aluminum plate within a smaller, insulated box inside the larger box and maintained at a constant temperature by using heating resistors that switch off when the plate becomes too hot. The feedback loops of both systems are closed-loop with their own thermistors and circuits.

Measuring the temperatures of the various components is accomplished by an independent circuit that employs AD590's as temperature probes. We monitor the Melcor temperature, the hot plate temperature, the temperature of the horn and the ambient temperature using the AD590 circuit. The temperature of the 1st stage is measured using a cryodiode mounted inside the LN dewar with a separate circuit because the cryodiode requires a precise bias current.

5.6 Computer Interfacing

After all the necessary data have been sampled and converted to RS232 format by the DAS it goes to the serial port of a PC. Knowing the format of the serial data coming in, we can reconstruct the sampled data for each channel. Using the LabVIEW visual programming language, I wrote a program to unpack the data coming in, display them real-time, and save them to an ASCII file with a time stamp for each sample.

The format of the data frames from the DAS is simple. Every frame begins with a synchronization signal which is a 16-bit word. Followed by the sync word are two 16-bit words that make up the 32-bit frame number. This is followed by all the sampled channels in 16-bit chunks as programmed by the EPROM. The first task of the LabVIEW program is to read in data from the serial port and look for two consecutive sync words, which we know ahead of time. Doing this, the program figures out the length of each frame in bytes. After this is done, the number of bytes corresponding to the length of each data frame is read at the next occurrence of the sync word. The program then checks to make sure that the first word read is the sync word. If not, the program tries to synchronize to the incoming stream of data once again. If everything is synchronized, the program simply reads in each frame and dissects it into pieces that represent the frame number, DC amp output, the 1st stage temperature, etc. Channels that are sampled more than once are averaged together.

The incoming data is continuously plotted on the screen so that the status of the telescope can be monitored continuously. One can run the program in "VIEW ONLY" mode, which displays the data but does not save them, or in "SAVE ASCII" mode, which saves each frame into an ascii file along with the universal time in decimal seconds. This allows us to reconstruct the pointing of the telescope on the sky knowing our latitude and longitude.

6. Results of Test Runs

We were able to put the entire system together and make several 24-hour runs. Most of the time, the input to the receiver was terminated to examine system noise. All of the secondary electronics such as the temperature regulation circuits work very well. We were able to achieve a regulation of 35°±0.1° over a 24-hour period for the components mounted on the hot plate. The dewar temperature was also stable for extended periods of time. Also trouble-free was the shaft angle encoder and the DAS along with the DC amplifier. All these components behaved expectedly.

Much to our dismay, however, the output of the receiver showed significant amount of periodic noise apparently coupled to the rotation. Fourier power spectrums show significant harmonics all the way up to the nyquist frequency. This is particularly bad because the signal we expect from the polarization of CMB is located at the 2nd harmonic at 0.2 Hz, or at twice the rotation frequency. Any amount of periodic noise at that frequency will not average down below the expected signal level as we expect random noise to do.

Also, mysterious spikes with no apparent periodicity appeared in our data. We were not able to identify the source(s) of these spikes. Even though the overall schematic of the experiment were put into operation, these and other problems prevented us from taking any good data of the sky. Repeated moisture problems due to insufficient weather-proofing of our instruments and winter weather at Berkeley gave us precious little time to make progress using extensive test runs.

7. Problems Encountered

The most significant problem of our experiment is the rotation noise. This arises because as the entire apparatus rotates slowly, vibrations are set up along the long horizontal beam and the tower synchronous with rotation which swamps the frequency channel that we expect the signal in. We have attributed the immediate cause of this noise on the mechanical stresses on the SMA connections going into the receiver. Since the gain of the system is so high, any amounted of physical stress at the input will have a large effect on the output. Some of the noise is also microphonic noise due to the shaking of the cables at the frequency of rotation. Using different cables and testing various cable support mechanisms, we determined that this effect is much smaller than the physical stresses at the input of the receiver.

Another problem encountered that prevented us from making any more significant progress is the dewar system. The dewar kept losing vacuum for various reasons and we had to repeatedly pump it down, which takes a few days of work. LN hold times would suffer as a result and we found ourselves without an operating 1st stage more often than we wanted.

Lastly, construction of extensions on the dish to serve as a ground shield made the mechanical design of the entire apparatus even more unstable. The large aluminum extensions would catch wind and shake the telescope to an unacceptable degree, causing large short timescale drifts in the signal due to connector stresses.

8. Needed Improvements

If the RoPE project is to remain viable, many improvements are needed. The entire mechanical design must be rethought to keep the telescope compact structurally. Instead of rotating about a slender shaft, one should invest in an industrial-quality turntable capable of smooth rotation with a significant amount of load on it. Such turntables are used in projects such as the Very Small Array (VSA). Also, the signal flow chain should be compacted to be immune to vibrations and stresses to a high degree. This can be accomplished by replacing the SMA connections with waveguides and having the entire receiver mounted into a self-contained rigid assembly.

The 1st stage cooling can be made more reliable and hands-free by employing a closed-cycle cryocooler. They do not use any cryogens and can be operated continuously at very low temperatures. A 15 K system will drastically reduce the system noise and the amount of time one needs to observe to reach a given sensitivity.

The problem of ground shielding does not have an easy industry solution. A construction of an even bigger windshield is not as practical. Going to higher frequencies will help reduce the overall physical scale of the experiments so that the wind-loading can be reduced. One can also construct ground shields that are physically isolated from the dish and the receiver so that any wind-loading on the shields will not result in the vibration of the rest of the telescope

No matter what future design is chosen, it is clear that to measure the polarization of the CMB, one needs to consider very carefully the experimental difficulties and how they should be dealt with. Extensive planning and designing is a must before one implements any aspect of the experiment.

9. Conclusion

In our attempt to measure the polarization of CMB, we have constructed a radio telescope and associated electronics and structures. Although we have not succeeded in making such a challenging measurement because of the problems outlined above, I have learned much about carrying out such an experiment.

It is clear that the polarization of CMB measurement will give us new, much needed, insight into the workings of the early universe. The experimental challenges are many, but the benefits of such a measurement is far too great. If anything, RoPE has been successful in teaching everyone involve in the project about facing up to such challenges and getting us to think about possible improvements and better designs which may be capable of measuring the polarization. Although I am disappointed that we were not able to take any real data, as a learning opportunity this project has been immensely satisfying.

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